Development of an Embrittlement Correlation Method Based on Understanding of Embrittlement Mechanisms

Background

Neutron irradiation embrittlement of reactor pressure vessel (RPV) steels of light water reactors (LWRs) is one of the most important ageing issues that need to be addressed for the structural integrity assessment of the reactor pressure vessels. Especially, for the aged plants for which continuing operation is expected, accurate prediction of the embrittlement is inevitable to verify the integrity of the reactor pressure vessels. CRIEPI has conducted research programs to understand embrittlement mechanisms by characterizing the microstructural changes in the irradiated RPV steels at nano-meter scale, and to develop a new embrittlement correlation method with high accuracy based on the understanding.

Objectives

To develop a model on the neutron irradiation embrittlement mechanisms of RPV materials of LWRs, to formulate the model, and to develop a new embrittlement correlation method for the Japanese RPV steels.

Principal Results

1. Formulation of embrittlment correlation model based on mechanistic understandings

By combining extensive data from the mechanical property tests, microstructural characterization of radiation damage using state-of-the-art techniques such as three-dimensional atom probe and positron annihilation, and the multi-scale computer simulations with the combination of several techniques such as molecular dynamics, kinetic Monte-Carlo, and dislocation dynamics, a new embrittlement correlation model was developed to describe the microstructural changes during irradiation and the resulting transition temperature shifts. Then the embrittlement model was formulated using rate equations as shown in Fig.1. Some new detailed models were introduced on the effect of solute elements, the effect of neutron flux and the process of damage accumulation.

2. Development of a new embrittlement correlation method

A new embrittlement correlation method, which we call hereafter “CRIEPI correlation method”, was developed by optimizing the coefficients of the rate equations using the surveillance data of the RPVs of all the nuclear power plants in Japan. A new plant specific adjustment method was also proposed to further optimize the predictions of the correlation method for the plants. The standard error of the differences between the Japanese surveillance data and the predictions is very much improved in the CRIEPI correlation method than in the current Japanese correlation method, JEAC4201, and the US correlation methods developed by NRC and ASTM as shown in Fig.2.

3. Comparison with the US surveillance data

The CRIEPI correlation method was tested by comparing the predictions for the US RPV steels with the US surveillance data which were not used to optimize the coefficients of the CRIEPI correlation equations. It was found that the CRIEPI correlation method has capability to predict the embrittlement of the US RPV steels with chemical compositions similar to those of the Japanese RPVs.

Part of this work was performed upon the request of the Federation of Electric Power Companies.

Future Developments

The Japanese embrittlement correlation method, JEAC4201, will be revised based on the results obtained by this work. Study on the mechanisms of embrittlement will be performed to further improve the accuracy of the correlation method in high fluence regime.

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Reference

N. Soneda, et al., “Study on the development of neutron irradiation embrittlement correlation method for the reactor pressure vessels of the light water reactors - Development of mechanism-based embrittlement correlation method,” CRIEPI Report Q05403, August 2006.

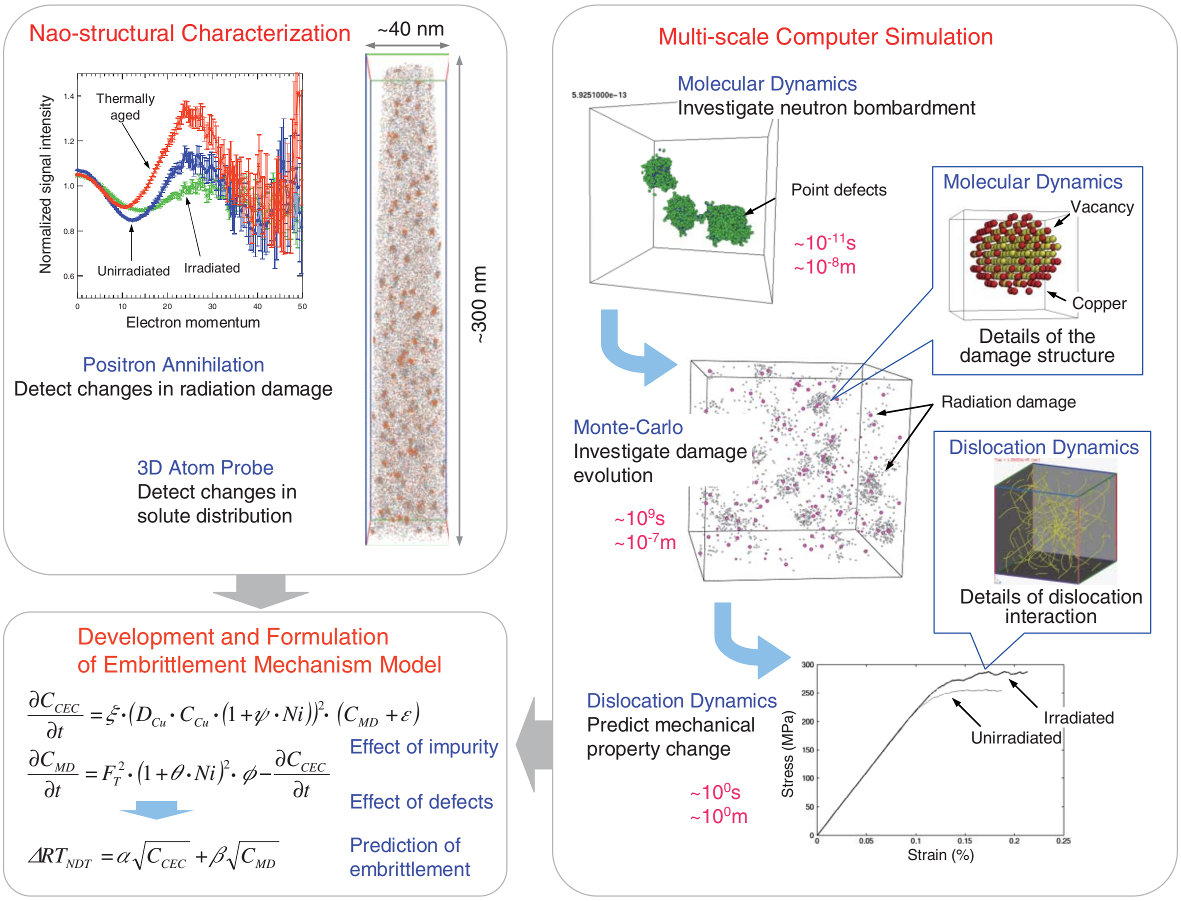

Fig.1 Formulation of the embrittlement model based on nano-structural characterizations and multi-scale computer simulations

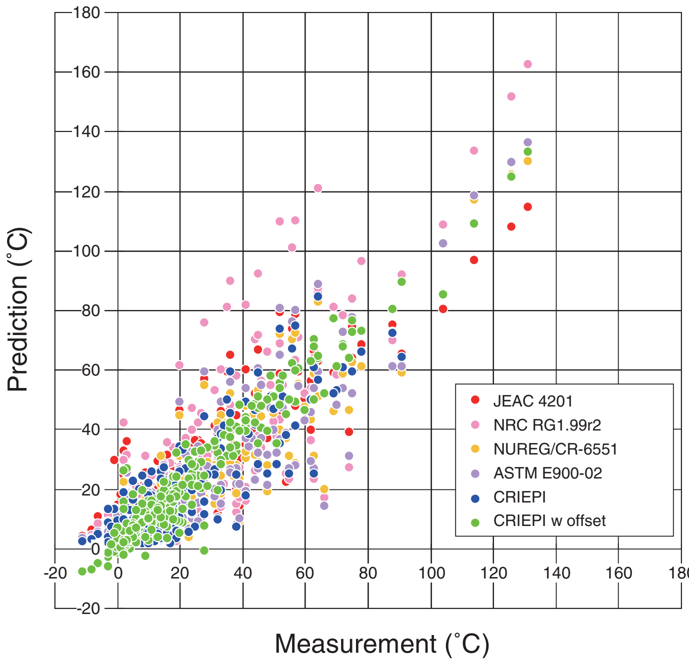

Fig.2 Comparison of the surveillance data and the predictions of the CRIEPI embrittlement correlation method. Standard error of the CRIEPI correlation in blue symbols is 10.2˚C, and this is further reduced to 6.1˚C as shown in green symbols when the plant specific adjustment is applied